Coastal and Submesoscale Process Studies for ASIRI and Data serving for ASIRI participants

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LONG-TERM GOALS

To determine the role of upper ocean processes, including mixing and advection, on freshwater dispersal, sea surface temperature, density structure, and air-sea heat fluxes in the Bay of Bengal. This is to understand the ocean's contribution to variability of the monsoons on intra-seasonal time scales.

OBJECTIVES

- Conduct modeling process studies to examine and evaluate lateral and vertical routes for dispersal of the freshwater in the Bay of Bengal.
- Provide shore support for ASIRI and OMM cruises.
- Conduct field campaigns in November (post-monsoon) and June (pre-monsoon) on board the R/V Revelle in the Bay of Bengal.
- Conduct optical measurements for field campaigns along with water sampling.
- Work with PIs in India to coordinate port access and training of Indian scientists during field effort.
- Help coordinate ASIRI PI meetings; facilitate collaborative papers.
- Analyze observational data to examine upper ocean structure and infer processes.
- Analyze satellite data for large scale signals in salinity and advection

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APPROACH

We carried out several numerical process experiments before the ASIRI –OMM cruises conducted on US R/V Revelle and Indian R/V Sagar Nidhi . In Nov-Dec 2013, June-July 2014 and August-Sept 2014 we also provided shore support guidance for field measurements. In addition to the PIs the key individuals on the following activities are:

Dr. Sanjiv Ramachandran (Research Associate, UMass Dartmouth), Jared Buckley (Graduate Student, UMass Dartmouth), Dr. Melissa Omand (Postdoctoral Investigator, WHOI), Gualtiero Spiro Jaegar (Ph.D. student, MIT/WHOI Joint Program).

The following activities were undertaken this year. Many of these were conducted in collaboration with other ASIRI investigators, particularly (ii) in collaboration with Andrew Lucas, Rob Pinkel (Wirewalker data), Jonathan Nash and Jen Mackinnon (ADCP data) Bob Weller and Tom Farrar (UCTD data and air-sea fluxes), and the chief scientists (Emily Shroyer and Amala Mahadevan) for Leg-2.

1. Simulations and analysis to estimate length scales of variability and guide deployment of wirewalkers in the November 2013 cruise on R/V Roger Revelle.
2. Field campaign November 2013 – Tandon and Ramachandran participated in Leg 1. Mahadevan (co-CS with Shroyer) and Omand in Leg 2 (see cruise reports for more detail).
3. Analysis of 2013 data
    a. Analyzed radiator pattern survey - UCTD/ADCP data collected during Leg 1. Submesoscale instability conditions.
    b. Analyzed large-scale survey – Leg 2 uCTD data. Barrier layers and subsurface warm patches.
    c. Apparent optical properties and nitrate
4. Estimating large-scale advection of salinity using Aquarius satellite surface salinity –and surface geostrophic velocities from OSCAR.
5. Shore support for June 2014 Revelle cruise and August 2014 Nidhi cruise.
6. Field campaign June 2014 – Participation by Omand and Spiro Jaeger (from WHOI), Ramachandran from UMassD. Measured optical properties and nitrate again.
7. Exploratory simulations to guide the August 2014 cruise (on R/V Nidhi).
8. Inter-comparison of R/V Revelle based air-sea fluxes with atmospheric fluxes from reanalyses.

RESULTS

1. Simulations to guide the deployment of wirewalkers in the November 2013 cruise aboard R/V Roger Revelle: We performed three-dimensional simulations of a frontal mixed layer for conditions typical of the returning monsoon period in November. The goal was to use simulations of virtual wirewalkers to guide their deployment in the Bay during November. Our results (Figure 1) show the triangular deployments on the edge of the front deform the most due to the high strain rates.

2. Analysis of data collected during the November 2013 cruise: Figure 2 shows a UCTD radiator survey conducted in a region of strong frontal gradients (after a storm) forced by weak wind stresses ($O(0.01N/m^2)$). During this survey we measured horizontal buoyancy gradients as large as $O(10^{-6}m/s^2)$, confined to shallow O(10m) mixed layers. The radiator survey presents an illustrative contrast to previous studies that have extensively documented the presence of submesoscale instabilities for deeper (O(100m)) mixed layers. The observed conditions present a unique opportunity to examine whether submesoscale instabilities can even occur for such shallow mixed layers. One of the signatures for submesoscale instabilities is negative values in the potential vorticity field, which implies conditions favorable to the onset of symmetric instability (SI). Before obtaining the potential vorticity field for SI in the Bay of Bengal, we de-tided the density and velocity signal (Figure 3) using the tidal solution provided by Andrew Lucas and Rob Pinkel from their analysis of the Wirewalker data. With the de-tided density and velocity we then calculated the different contributions to the potential vorticity field. In Figure 4 we show the results of this calculation using the velocity data from the sentinel mounted on the side of the ship. Both lateral density gradients and the vorticity field give rise to patches of negative potential vorticity, which are O(10m) thick and O(1-5km) wide. Further analysis (plot now shown) suggests the 8-km smoothed density and velocity fields meet the necessary condition for SI (Thomas *et al.* 2013). We are currently exploring the generation of negative PV during the radiator survey using submesoscale-resolving three-dimensional numerical simulations, initialized with temperature-salinity sections from the survey.

3. Analysis of long sections with high-resolution sampling from Leg 2 of the November 2013: This field campaign provided an opportunity to examine the upper ocean structure in detail (Figure 5) over a large region in the Bay of Bengal. We observed a strong salinity gradient in the surface layer over the north-south extent of the Bay. Density of the surface mixed layer (ML) is strongly controlled by density. The ML overlies a barrier layer, the thickness of which varies between 5m (to the south) and 50 m (to the north). We identified two separate sources of freshwater from their T-S characteristics – the freshest water we sampled at 18N was from the Irrawaddy river delta, whereas the freshwater lying to the west was from the Ganges-Brahmaputra and had likely made its way along the coast. The stratification beneath the mixed layer is extremely strong – values of the buoyancy frequency N were as large as $0.06\ s^{-1}$. Scales of variability are analyzed through spectra.

4. Apparent and inherent optical properties and nitrate from Leg2 of November 2013 : Figure 6 shows the downwelling irradiance measured from a hyperspectral radiometer. We found that the deeply penetrating blue-green wavelengths are absorbed strongly near 50 m depth, corresponding to the location of a subsurface maximum of Chl and CDOM. Figure 7 shows T-S characteristics, and spatial distributions of Chlorophyll fluorescence, colored dissolved organic matter (CDOM), and apparent oxygen utilization (AOU). It is evident that different water masses, as defined by their different T-S characteristics also possess different optical and biological characteristics. In general, the cold water observed episodically near the western flank of the cruise was rich in fluorescence, low in CDOM and had low AOU, indicating that production is outcompeting respiration in these waters.

5. Exploratory simulations to guide the August 2014 cruise (on the Nidhi): We performed some idealized simulations to simulate the response of the upper-ocean dynamics under conditions similar to those observed during the June 2014 cruise aboard the Indian vessel Nidhi. The simulations illustrate the effects of “upfront winds,” or winds that result in the advection of lighter over denser water. We initialized the simulations with idealized T-S profiles and winds characteristic of the

summer Monsoon, as inferred from an earlier cruise in June aboard the Roger Revelle. Figure 8 shows the temporal evolution of the near-surface potential vorticity and the potential density fields. The rapid advection of the front due to Ekman transport is seen in the movement of the chosen isopycnal, sigma_t = 20.3 kg/m^3. The potential vorticity (PV) field is mostly positive as upfront winds, unlike downfront winds, do not destroy PV.

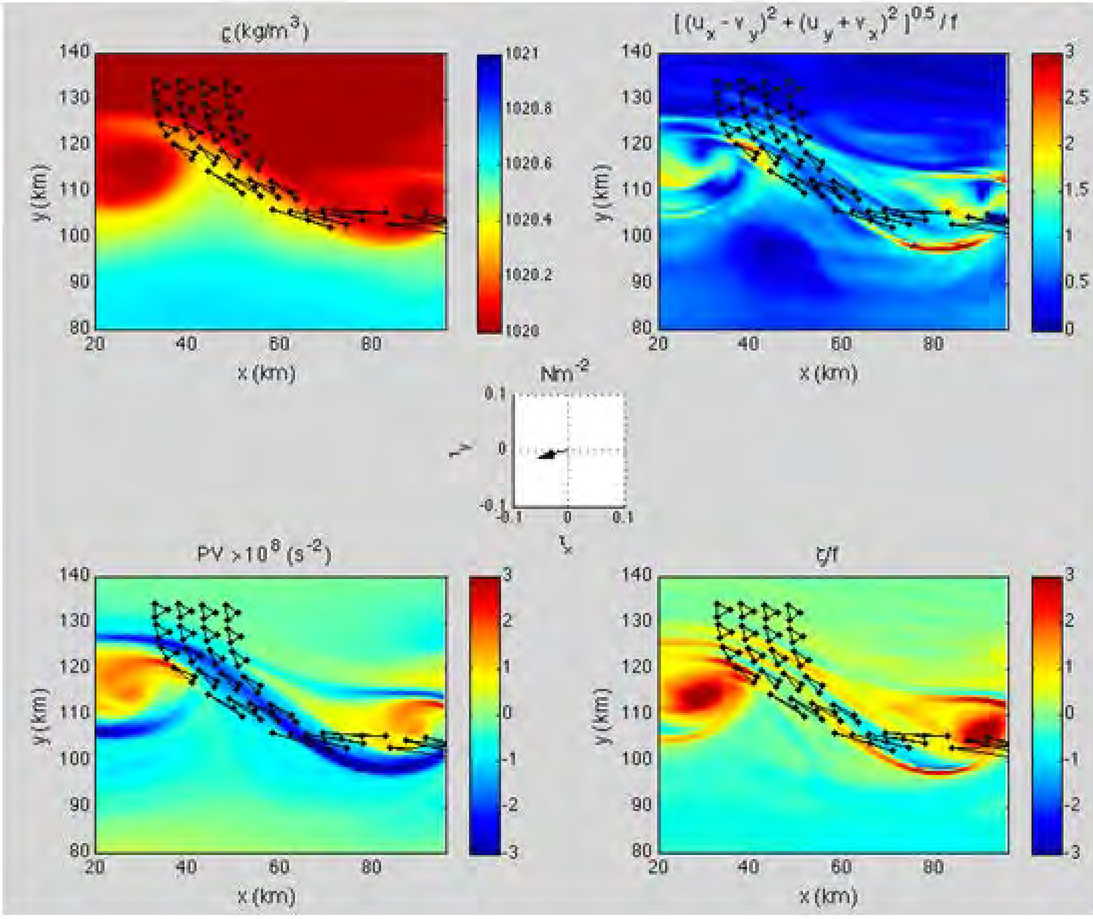
6. Shore support for June 2014 Revelle cruise and August 2014 Nidhi cruise: Jared Buckley and Amit Tandon at UMass Dartmouth provided shore support using a multitude of remote sensing data and oceanic and atmospheric model output as well as blended products, which were made available to the chief scientists and the scientists onboard Revelle and Nidhi. Figure 9 shows one such image, which combines remotely sensed data with models and available in-situ data. It shows Sea Surface Salinity, Sea Surface Height Anomaly, and OSCAR currents for June 20, 2014. SSS uses along track data from NASA Aquarius Satellite and Seaspray BoB glider, SSHA is from CCAR gridded altimetry, and OSCAR currents are 5 day averages.

7. Analysis of satellite salinity data: The time rate of change of salinity in the Bay of Bengal is largely due to advection. This was calculated using surface velocity fields from OSCAR and surface salinity from Aquarius. The salinity data was advected on virtual particles using the velocity fields and the salinity on particles was updated when new satellite data was available. The advective changes in salinity were differentiated from the change in salinity due to sources/sinks or other processes. The largest non-advective changes in salinity occur in the northern Bay during Oct-Dec, which is when the greatest freshwater input occurs. Since evaporation-precipitation makes a negligible contribution, it suggests that the losses of freshwater due to subduction or mixing are seasonally coincident with its input.

8. Inter-comparison of R/V Revelle based air-sea fluxes with atmospheric fluxes from reanalyses. : Figure 10 shows the inter-comparison of ship measured and atmospheric reanalysis air-sea fluxes for ASIRI leg 1 (November 2013). The following reanalysis products were compared; MERRA, ECMWF ERA-Interim, NCEP/DOE, and NCEP/NCAR, for the grid points closest to Revelle's location. The largest differences are in latent heat fluxes as shown in Figure 9. This ongoing work forms the basis of Jared Buckley's Master's thesis.

PUBLICATIONS

A. J. Lucas, E. L. Shroyer, H. W. Wijesekera, H. J. S. Fernando, E. D'Asaro, M. Ravichandran, S. U. P. Jinadasa, J. A. MacKinnon, J. D. Nash,R. Sharma, L. Centurioni, J. T. Farrar,R. Weller, R. Pinkel, A. Mahadevan, D. Sengupta and A. Tandon, Mixing to Monsoons: Air-Sea Interactions in the Bay of Bengal. Eos, Transactions American Geophysical Union Volume 95, Issue 30, pages 269–270, 29 July 2014.



<u>Figure 1:</u> Deformation of "virtual wirewalkers" in a simulation of a front initialized with downfront winds and T-S profiles from Argo floats in the central Bay of Bengal. The dots denote deployments of virtual wirewalkers in triangular configurations, used to estimate the vorticity. Clockwise (from top left): (i) potential density, (ii) lateral strain (scaled with Coriolis parameter) (iii) vertical component of vorticity scaled with Coriolis parameter; and (iv) potential vorticity. The inset in the center shows the magnitude and orientation of the wind stress vector.

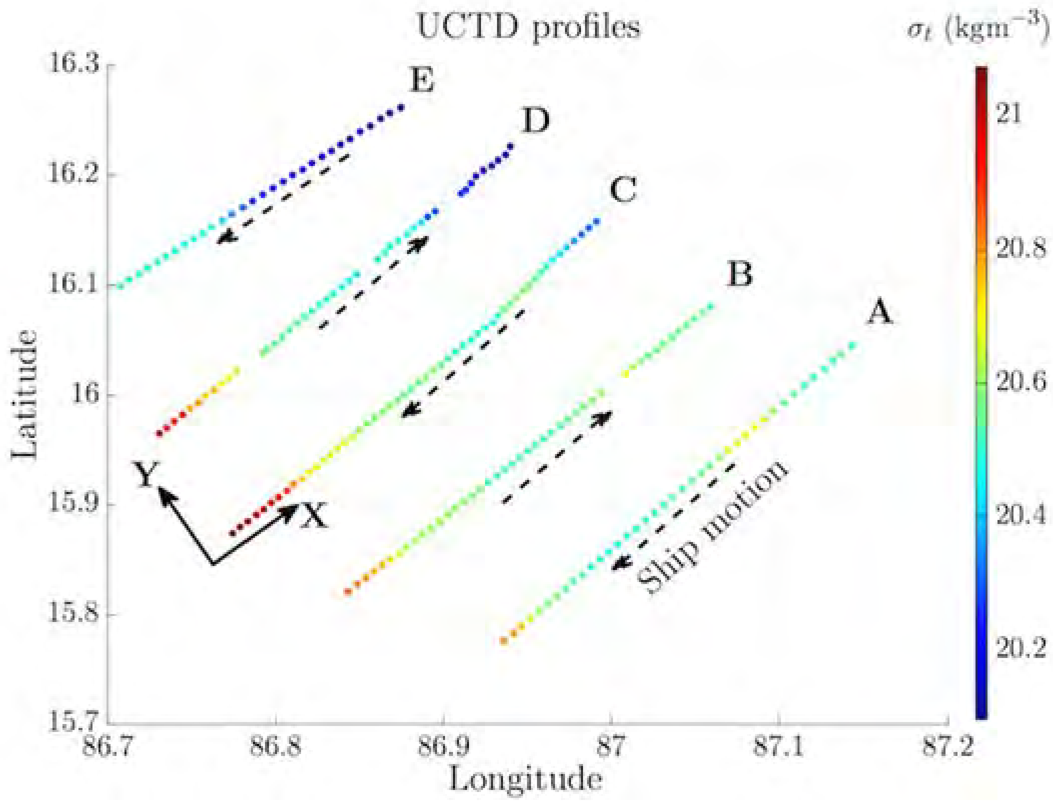
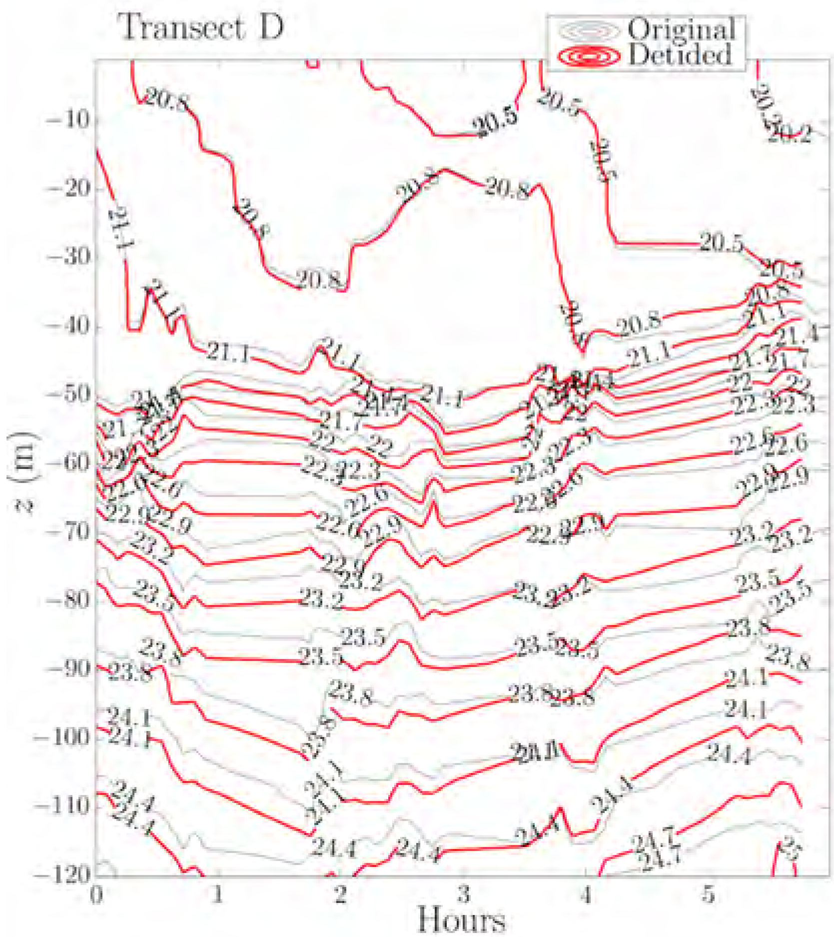
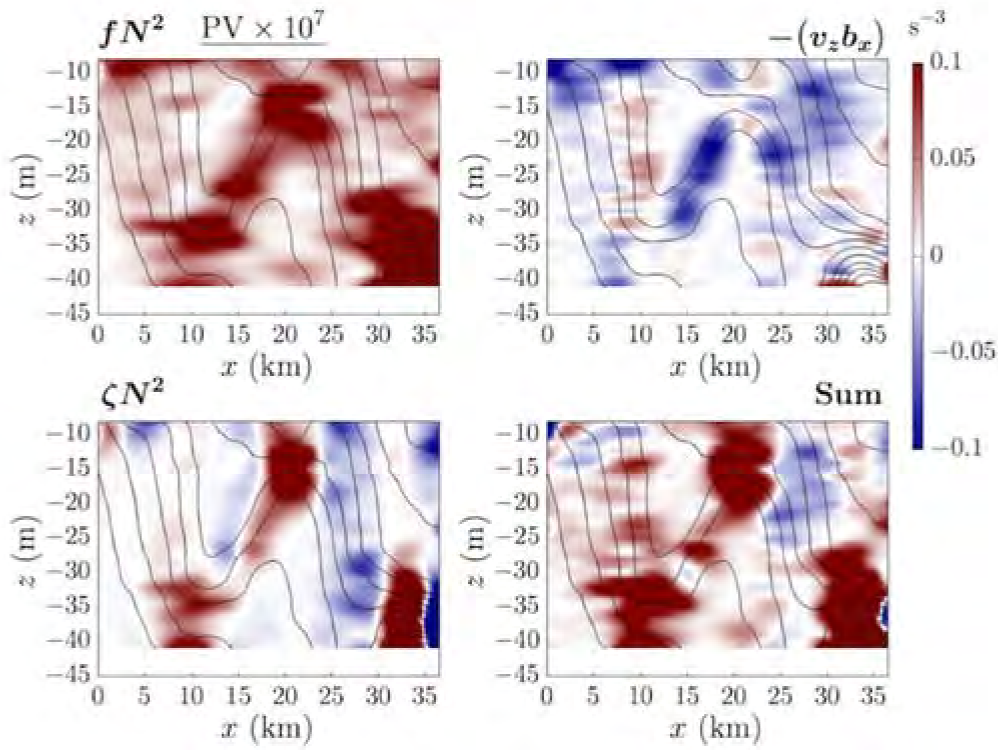


Figure 2: ***Locations of UCTD profiles for the tow-yo radiaton survey. The X and Y axes shown describe the coordinates in the analysis of the field data (see Fig. 4).***



<u>Figure 3:</u>* *Isopycnals for one of the radiator-pattern transects before and after removing the M2 signal. The tidal solutions for the density field were obtained from analysis of the wirewalker data (by ASIRI PIs Andrew Lucas and Robert Pinkel, Scripps Institute of Oceanography).



<u>Figure 4:</u> Contributions to the potential vorticity for transect D in the radiator survey. Clockwise (from top left): (i) Vertical shear contribution -v_z b_x (ii) Planetary vorticity contribution fN^2 (iii) Vertical relative vorticity contribution (v_x – u_y)N^2; and (iv) sum of the three contributions.

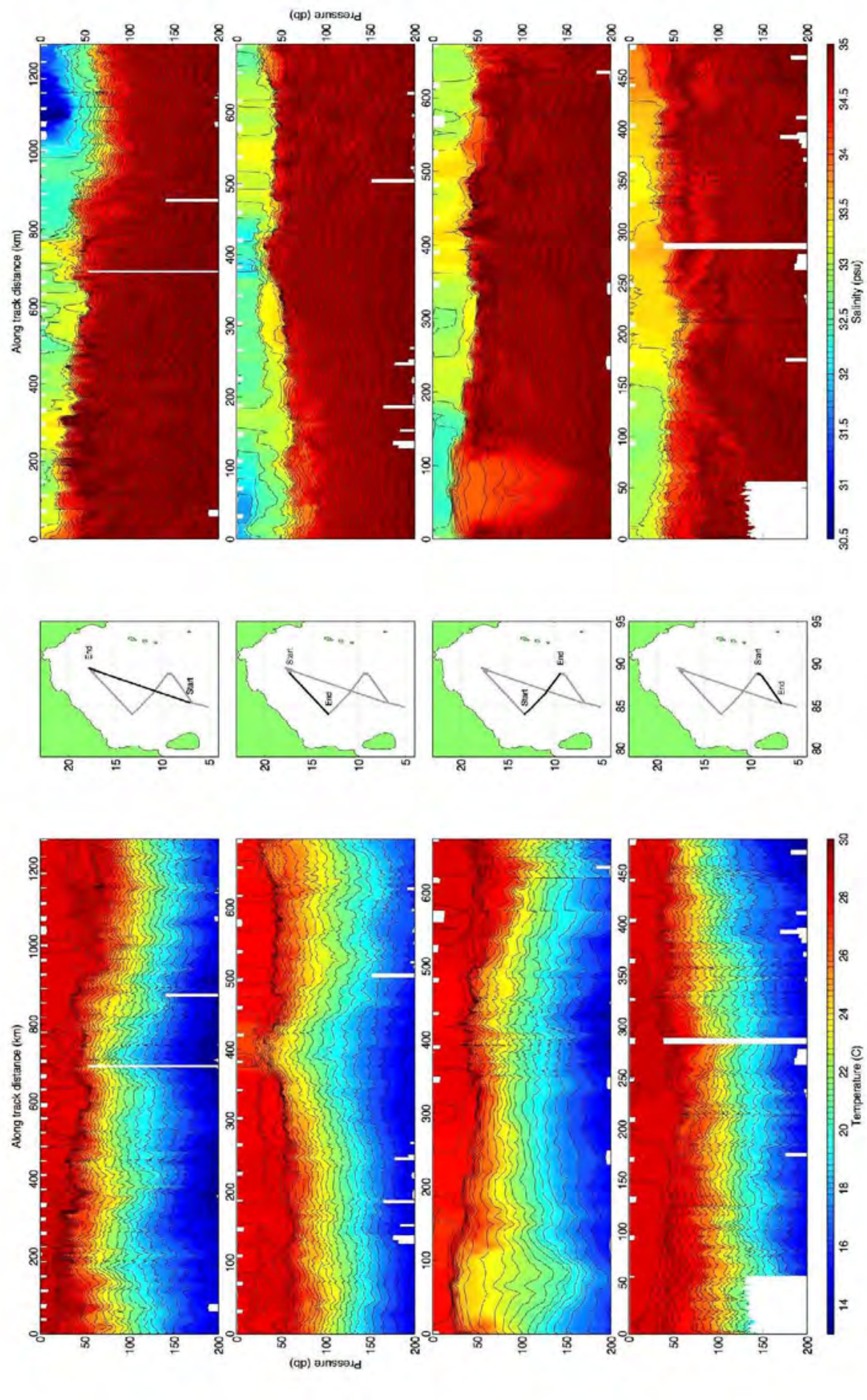


Figure 5: Vertical section of temperature (left) and salinity (right) with density in black contours, from 4 long tracks surveyed in Leg 2 (November 2013) from the R/V Revelle. The cruise track corresponding to each pair of T,s sections is shown highlighted at center. The sections are constructed from underway CTD (about 1500) and CTD profiles (80 stations.

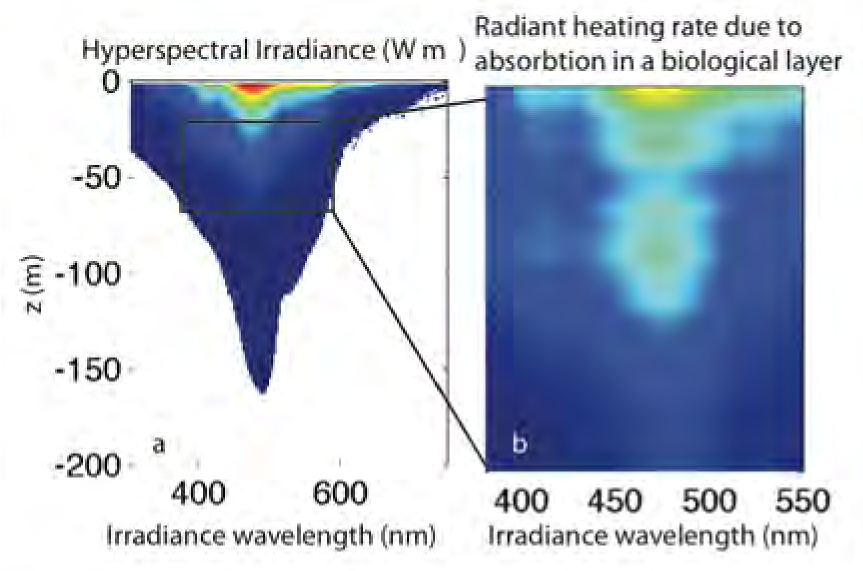


Figure 6: a) Downwelling irradiance measured from a RAMSES hyperspectral radiometer. Intensities ranging from 200 near-surface to 0.0001 W/m2 were observed on 256 channels spanning 350 to 1500 nm. b) The vertical derivative of the downwelling light is proportional to the radiant heating rate at depth. This figure shows that deeply penetrating blue-green wavelengths are absorbed strongly near 50 m depth, corresponding the location of a subsurface maximum of Chl and CDOM

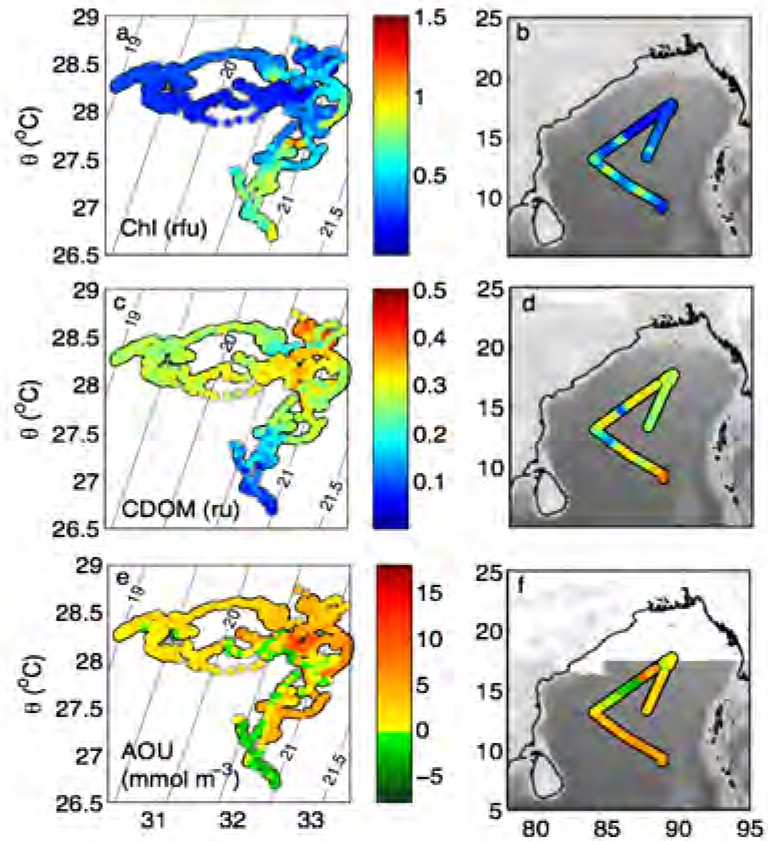


Figure 7: Temp-Salinity diagrams (left columns) and spatial location (right columns) of a-b) Chlorophyll fluorescence, c-d) colored dissolved organic matter (CDOM), and e-f) apparent oxygen utilization (AOU). These data reflect a subset of the cruise tracks during Leg 2 of the December cruise. It is evident that different water masses, as defined by their different T-S characteristics also possess different optical and biological characteristics. In general, the cold water observed episodically near the western flank of the cruise was rich in fluorescence, low in CDOM and had low AOU, indicating that production is outcompeting respiration in these waters.

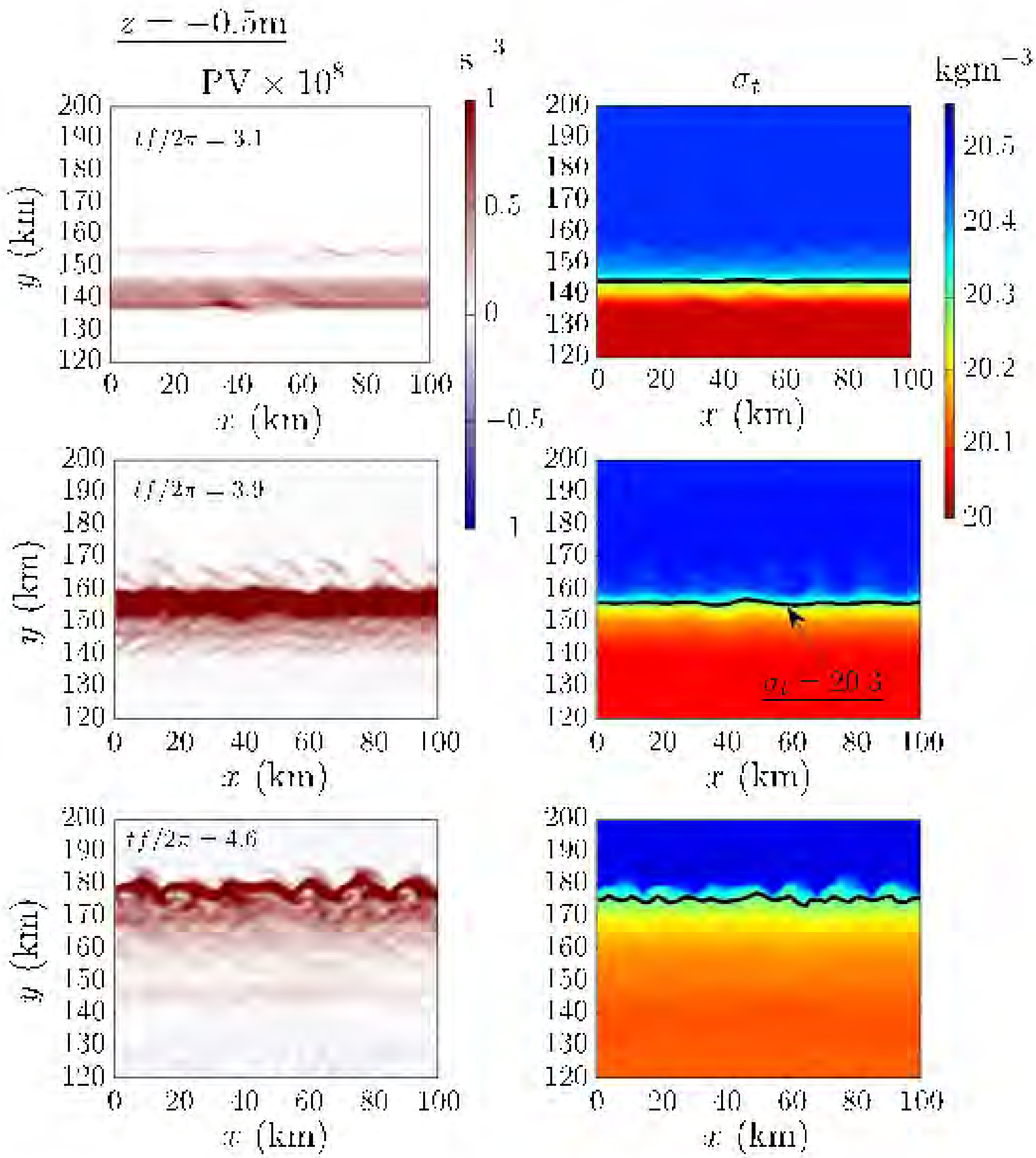


Figure 8: ***Advection of front by upfront winds for summer-monsoon conditions in the Bay of Bengal. The plots show the near-surface evolution of the potential vorticity (left) and the potential density (right). Note the rapid advection of the isopycnal denoted by a black line.***

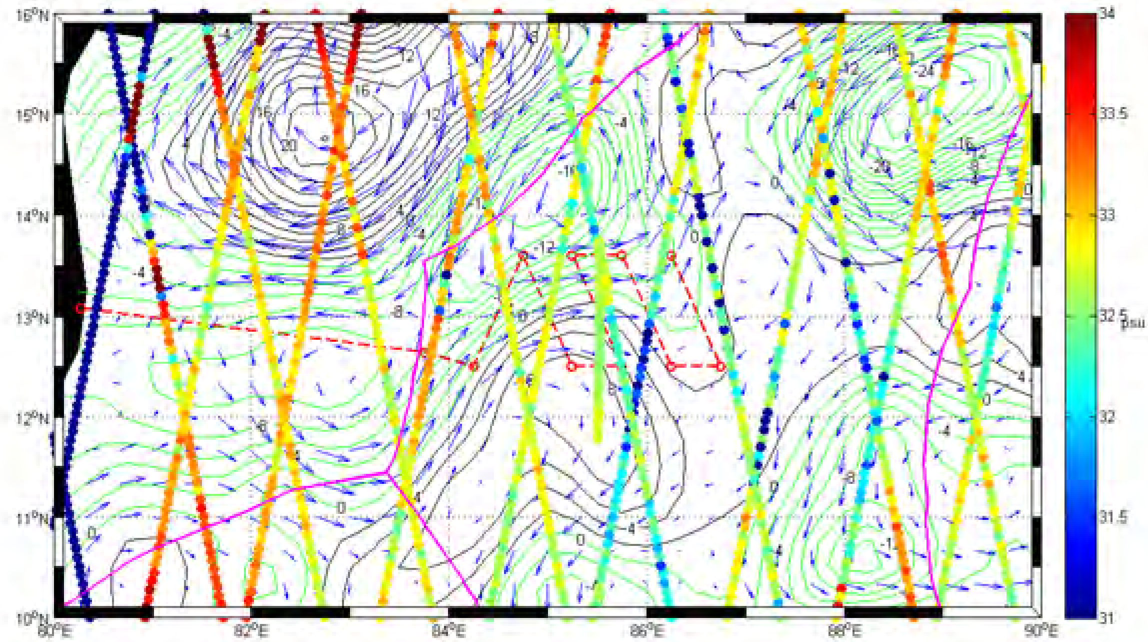


Figure 9: Cruise guidance plot on June 20th 2014 which combines multiple remotely sensed data with models and available in-situ data. It shows Sea Surface Salinity (SSS, color fill), Sea Surface Height Anomaly (SSHA, contours in green are less than zero and in black are greater than zero in 2cm intervals), and OSCAR currents (quiver) from remote sensing for June 20, 2014. SSS uses along track data from NASA Aquarius Satellite and Seaspray BoB glider, SSHA is from CCAR gridded altimetry, and OSCAR currents are 5 day averages. Also plotted is the EEZ in magenta and the proposed R/V Revelle waypoints in red.

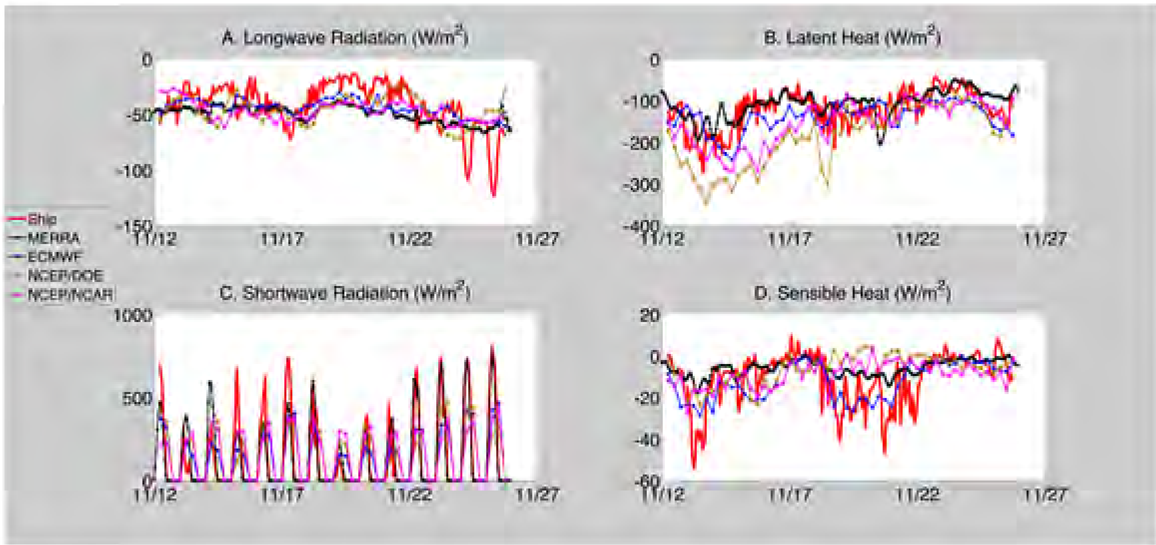


Figure 10: Inter-comparison of ship measured and atmospheric reanalysis air-sea fluxes for ASIRI leg 1 (November 2013). Reanalysis products compared are MERRA, ECMWF ERA-Interim, NCEP/DOE, and NCEP/NCAR, for A) longwave radiation, B) latent heat flux, C) Shortwave radiation, and D) Sensible heat flux. Reanalysis data are obtained for the model gridpoint closest to the location of the ship.